BINAURAL LOCALIZATION OF TONES AS DEPENDENT UPON DIFFERENCES OF PHASE AND INTENSITY[1]

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HISTORICAL SETTING

The reader will find the literature on the binaural localization of sound discussed by Pierce[2] and by Ferree and Collins[3].

In referring to the literature certain terminological usages need to be kept in mind. Hearing or localization is *monaural* if only one ear functions in the process; it is *binaural* if both ears function together. Stumpf's[4] terminology makes a finer distinction. Hearing is *monotic* if only one ear functions in hearing; it is *diotic* if both ears function together in the same manner, *i. e.*, if the same tone or tones are heard by both ears; it is *dichotic* if both ears function simultaneously for different tones, *i. e.*, if different tones or complexes of tones are heard simultaneously by the two ears.

The original problem of binaural hearing has arisen out of the demonstration of the fact that, although there may be monaural localization of sound, binaural localization is more accurate. This fact is brought out in the studies of Angell and Fite,[5] Angell,[6] Starch,[7] and Klemm.[8]

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[1]From the Psychological Laboratory of Clark University. The experiments herein reported were performed subsequently to certain experiments by the writer at the University of Iowa. The monograph reporting these experiments (*Univ. Iowa Studies in Psychol.*, No. 8, 1921) is now in press and explicit reference can not therefore be made to it.

One general way in which the present studies differ from the Iowa experiments is in the appeal made to introspective control of the image of localization and the process of localizing. It is unfortunate that limits of space prevent the printing of complete introspective data, as well as the historical orientation of the problem. All these matters are presented fully, however, in a bound manuscript report of these studies, which is filed under the same title in the Clark University Library, and can be borrowed under the usual courtesies of library exchange.

[2]A. H. Pierce, *Studies in Space Perception*, 1901.

[3]C. E. Ferree and R. Collins, An Experimental Demonstration of the Binaural Ratio as a Factor in Auditory Localization, *Am. J. Psychol.*, 1911, 22, 250-297.

[4]C. Stumpf, Ueber zusammengesetzte Wellenformen, *Ztsch. f. Psychol.*, 1905, 39, 276.

[5]J. R. Angell and W. Fite, The Monaural Localization of Sound, *Psychol. Rev.*, 1901, 8, 225-246.

[6]Angell, Further Observations in the Monaural Localization of Sound, *ibid.*, 449-458.

[7]D. Starch, Perimetry of the Localization of Sound, *Psychol. Rev. Monog.*, 1905, No. 28, 1-45; 1908, No. 38, 1-55.

[8]O. Klemm, Untersuchungen über die Localisation von Schallreizen, 2 Mitteil., *Psychol. Studien*, 1913, 8, 497-505.

The further problem has consisted in a determination of the nature of the binaural integration that operates in these finer localizations of binaural hearing. Wilson and Myers[9] have sought to explain this integration as peripheral and occurring by way of bone-conduction of the sound from one ear to the other. Others (*e. g.* Stewart[10]) have sometimes made use of this principle. There have, however, been numerous objections to the assumption of the effectiveness of bone-conduction. The reader should in this connection consult Cross and Goodwin,[11] More,[12] Peterson,[13] and Klemm.[14]

Peterson and Klemm are for this and other reasons forced to a theory of central integration, a type of explanation which is further supported by Watt.[15] The necessity for integration at the center is apparent when it is demonstrated that stimulation of the two ears is readily discriminated: Cross and Goodwin,[16] Peterson,[17] and Baley.[18]

Apart from certain earlier suggestions that localization might be dependent upon tactual sensations of the shell and drum of the ear, upon stimulation of the semi-circular canals, or upon "original special differences of the ears," there have been three principal theories of binaural localization.

(1) In the first place there is the theory that the localization of direction depends upon the relative intensive differences of a sound as it reaches the two ears. This theory seeks to express the angle of directional localization as a function of the binaural intensive ratio. The view is held, with various degrees of generality, by Angell and Fite,[19] Angell,[20] Starch,[21] Wilson and Myers,[22] Ferree and Collins,[23] Stewart and Hovda,[24] and Klemm.[25]

(2) The opponent theory seeks to explain binaural localization as a function of the two sounds in their phase-relations as they are presented

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[9]H. A. Wilson and C. S. Myers, The Influence of Binaural Phase Differences in the Localization of Sound, *Brit. J. Psychol.*, 1908, 2, 362-386.

[10]G. W. Stewart, The Theory of Binaural Beats, *Phys. Rev.*, N. S., 1917, 9, 514-528.

[11]C. R. Cross and H. M. Goodwin, Some Considerations Regarding Helmholtz's Theory of Consonance, *Proc. Am. Acad. Arts & Sci.*, 1891, 27, 1-12.

[12]L. T. More, On the Localization of the Direction of Sound, *Phil. Mag.*, 1909 (6 ser.), 18, 308-319.

[13]J. Peterson, The Nature and Probable Origin of Binaural Beats, *Psychol. Rev.*, 1916, 23, 333-351.

[14]Klemm, *op. cit.*, 4 Mitteil., *Arch. f. d. ges. Psychol.*, 1920, 40, 117-146. Referred to hereafter as "Klemm 4."

[15]H. J. Watt, *The Psychology of Sound*, 1917. A Theory of Binaural Hearing, *Brit. J. Psychol.*, 1920, 11, 163-171.

[16]*Op. cit.*

[17]*Op. cit.*

[18]S. Baley, Versuche über die Lokalisation beim dichotischen Hören, *Ztsch. f. Psychol.*, 1914, 70, 347-372.

[19]*Op cit.*

[20]*Op. cit.*

[21]*Op. cit.*

[22]*Op. cit.*

[23]*Op. cit.*

[24]G. W. Stewart and O. Hovda, The Intensity Factor in Binaural Localization, *Psychol. Rev.*, 1918, 25, 242-251.

[25]Klemm, *op. cit.*, 3 Mitteil., *Arch. f. d. ges. Psychol.*, 1918, 38, 87.

at the two ears: a theory of phase-difference. Rayleigh[26] is the exponent of this theory. He holds that difference of phase is the principal condition of localization for the lower pitches. More and Fry[27] have a similar conclusion. Bowlker[28] reports multiple localizations as a function of phase-difference, Stewart[29] appeals to phase-difference as the principal factor in localization. Hartley[30] works out the mathematical relation between localization and phase-difference.

It would seem in general that psychologists have tended to turn to intensity and the physicists to phase-difference as the primary condition of localization. The fact that theories of phase-difference ordinarily take more account of the intensive factor than do the intensive theories of phase is due undoubtedly to the greater recency of the theories of phase.

(3) Klemm[31] has recently shown that, in case of a sound of short duration, the relative times of arrival of the sound at the two ears may condition localization. He finds that under the conditions for unitary localization priority of presentation is equivalent to the greater effectiveness secured by greater intensity, and thus seems to reduce both intensity and priority to some common factor of auditory effectiveness. In the writer's opinion it is possible that priority in phase may also ultimately be reduced to the same common denominator.

Binaural Localization of a Tone With Closed Tubes

In this first experiment the usual procedure with closed tubes was carried through in order to verify previous results with our observers and conditions and to obtain introspections with them. The following served as observers: Professor E. G. Boring (*B*), Dr. C. C. Pratt (*C*), Miss M. Bates (*A*), and the writer (*D*), all members of the laboratory group in experimental psychology. Dr. M. Yokoyama acted as experimenter for *D*.

Description of Apparatus and Method of Procedure

Two glass tubes of inside diam. of 5-16 in. were mounted so that each was perpendicular to the outside face of a 512 d. v. electric tuning fork, driven by a master fork of 256 d. v. encased in a padded box. These glass tubes were connected by rubber tubing of the same diam. to stethoscopic binaurals in a second room. In the latter room was a large table upon which a semicircumference of a radius of 2m. was marked off. Pasteboards with appropriate numbers were erected at intervals of 10° on the semicircumference to serve as localizing cues for the *O*, who with the binaurals in his ears was seated at the center of the circle. One of the rubber tubes in the first room was cut in two, and two glass tubes, each 90 cm. in length and one telescopically containing the other, were inserted in the breach, so that the length of this conductor could be reduced or increased by sliding the inner tube in or out of the larger. The larger tube was secured to a table upon

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[26] Lord Rayleigh, On Our Perception of Sound Direction, *Phil. Mag.* (6 ser.), 1907, 13, 214-232.

[27] L. T. More and H. S. Fry, On the Appreciation of Phase of Sound Waves, *Phil. Mag.* (6 ser.), 1907, 13, 452-459.

[28] T. J. Bowlker, On the Factors Serving to Determine the Direction of Sound, *Phil. Mag.* (6 ser.), 1908, 15, 318-332.

[29] Stewart, The Function of Intensity and Phase in the Binaural Location of Pure Tones, *Phys. Rev.*, N. S., 1920, 15, 425-445.

[30] R. V. L. Hartley, The Function of Phase Difference in the Binaural Location of Pure Tones, *ibid.*, N. S., 1919, 13, 373-385.

[31] Klemm 4.

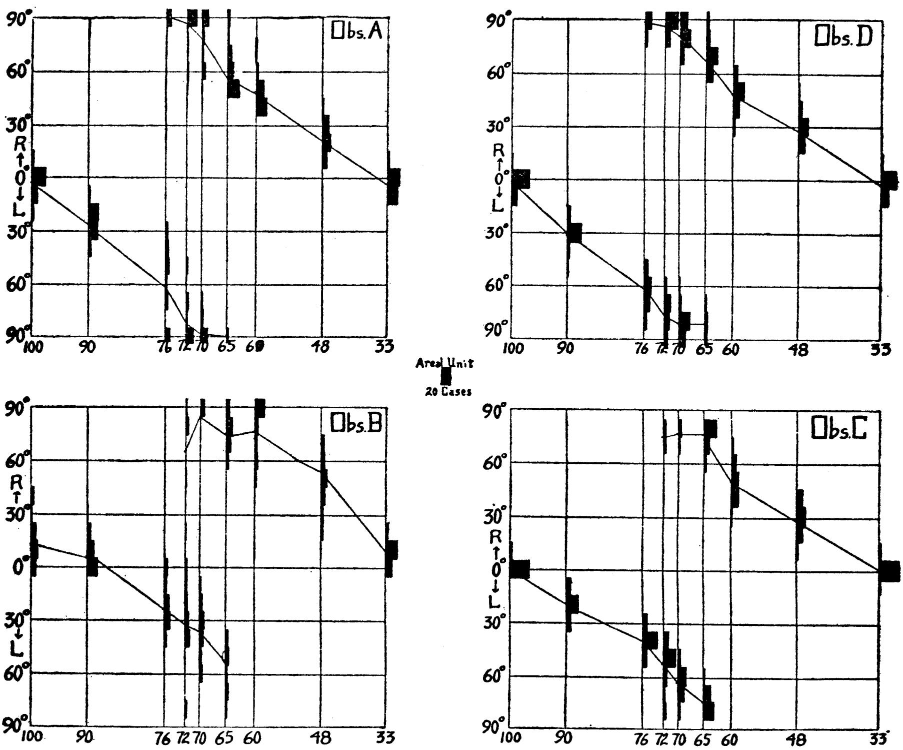

Fig. 1. Closed tube localization. Graphs of four *O*s, showing distribution of frequencies of localizations in degrees right and left of the median plane for the positions indicated on abscissa (cm.). Abscissa values are in terms of the scale of the apparatus (see text) and represent phase-differences of the tone at the two ears. The width of each chart, 67 cm., is the wave-length of the tone, 512 d. v., thus all phase-relations occur once in each chart. The areal unit representing the size of a block of 20 judgments for *A*, *C*, and *D*, should be read as 10 judgments for *B*. Double images occur at positions 76-65.

which a meter stick was fastened parallel with the tube. The open end of the inner tube served to indicate the position which had previously been determined by experimentation. Nine positions, selected because of the peculiar advantages they offered for studying our problem, were used.

With the *O* in position and the forks sounding, the apparatus was set for one of these positions. The *O* put the binaurals to his ears, localized the sound, removed the binaurals and wrote his judgment on a paper before him. The stimuli were presented in the order in which the numbers appear in the extension of the numerical value of π ('chance' order).

Results

The general schema for localizing was as follows. The *O* was told that he would be presented with an auditory stimulus the position of which he was to report in terms of degrees right or left of the median plane of his head. "Zero" represented any position in the median plane, "left 90" and "right 90" stood for positions in the aural axis at the left and right respectively, while intermediate positions were indicated by "left 10", "left 20", *etc.*, or "right 10", "right 20", *etc.*

Graphical Presentation

The quantitative results of the experiment are shown in Fig. 1. Here ordinates are drawn for the nine abscissa values experimented with. The abscissa is recorded in cm. of the scale attached to the telescopic tubes (*v. supra*). Ordinates are degrees right and left of the median plane. Upon each ordinate is erected a histogram showing the frequency of localizations which the *O* gave for the particular setting of the tubes. The areal scale is shown by the blocks at (70, R50) and (70, R20) in the chart for *B*, each of which represents a single case. Constancy in localization is indicated inversely by the amount of scatter of the histograms. The diagonal lines connect the averages of the distributions. The direction of the lines indicates the course of the image.

The graphs of the four *O*s are much alike. Localizations are median at the positions 100 and 33. From 100 to 76 the localizations are at the *O*'s left, from 72 to 65 double localizations occur, and from 60 to 33 the localizations are always at the right. The distance from one median localization to another is approximately 67 cm., which equals at 70° F. one wave-length of the tone used.[32] Double localizations take place one wave-length apart at points midway between the median localizations, a fact which we determined by further experimentation.[33]

A fair indication of the accuracy in localization is shown by the averages of the mean variations of the localizations for the four *O*s: *A*, 7.1°; *B*, 11.5°; *C*, 5.1°; and *D*, 5.6°.

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[32] *Cf.* Bowlker, *op. cit.*; Wilson and Myers, *op. cit.*

[33] Bowlker's "two-image" points; *op. cit.*, 323.

B shows a decided tendency to refer the sound to his right. Localizations were frequently reported in the aural axis at his right but it is seldom indeed that they occur beyond 'left 50'.[34] An examination of *B*'s ears revealed that the left orifice is of slightly greater diameter than the right; hence it may be that the manner in which the stethoscopic binaurals fitted into these orifices in some way influenced localization. In testing his ears with an audiometer, no noticeable difference in hearing acuity was found.

Frontal and Lateral Localizations

The graphs show that the position of the image is most accurately determined when the localization is median and is increasingly less accurate as the localizations become more and more lateral. This inaccuracy according to the introspective evidence is due to two facts: failure to distinguish the position of the image both on account of its diffuseness and its vacillating nature, and on account of the failure of the *O*s to make accurate references to their localizing schemata. Since the schemata of our *O*s were visual, it is not surprising that peripheral localizations should have been inaccurate, since the visual field is poorly defined in this region.

In general it may be said that the lateral localizations are more difficult and less immediate than the frontal. The lateral image tends to be more diffuse and vague than the frontal, but is not necessarily so.

For example, *A* always made some such report as the following for the frontal image: "The frontal localization was immediate. I was fixating before me and heard the tone in the exact spot where I was focussing." "I was aware of kinaesthesis of my head giving the impression of left, so I said 'left 90.' This is much more difficult and the judgment is not immediate." Reports for all of *A*'s lateral localizations are similar.

B was less consistent, but always found the lateral localizations the more difficult. He reported once of a frontal localization: "The visual median image is small and intense, but easily localized;" and another time: "The visual median image is vague and of indefinite extent, but easily localized." The typical report for a lateral image describes it as "vague, diffuse and indefinite, and difficult to localize."

C always found the frontal and lateral images equally "clear" and "intense," although the lateral images involved "greater effort due to an inability readily to comprehend the visual schema." For example, *C* once reported as a summary of his experience: "At first the eyes are in a resting position, *i. e.*, looking in front of me, and the visual schema usually includes the area around zero. Now if the stimulus sets up an impression congruent with this kinaesthetic and visual set, the localization is naturally simple. If the impression is not congruent with this set, the visual schema must readjust itself and eye-movement sets in. If this movement is extensive there is awareness of kinaesthetic strains (meaning difficulty), though the actual localization is not difficult."

D, the most practised *O*, could distinguish no differences in the frontal and lateral images, except that the lateral tended to shift more readily under attention.

None of the lateral images compared was in the aural axis. When the image reaches the aural axis it is described by *A* as "more intense auditorily." For *B* the "visual context" was indefinite, "a vague misty blur."

[34]Hartley, *loc. cit.*, shows mathematically that the image of a 512 v. d. tone should move laterally as far as the aural axis of the observer.

C characterized the tonal image as "very intense," "elliptical," and "scattered." *D* said it was "scrambled, diffuse, piled up with an umbrage of surplus sound making it difficult to analyze."

That lateral localizations are more difficult to judge is Bowlker's view.[35] He states that within 20° on either side of the median plane localization is very accurate but that beyond 50° it may vary 10° or more.

Introspective Analysis

Localization of sound by means of conducting tubes is usually regarded as a simple process, in which the acoustic image appears to the *O* to be at his front, back or side, and in which he makes his report correspondingly. Psychologically the process of localizing is not simple.

For *A*, who kept her eyes open continually, the process of localizing the tone ran itself off in the following manner (analysis of 7 complete reports). (1) Very indefinitely localized perception of the tone began the process in all cases. (2) Then a movement of the eyes, a kinaesthetic pattern, indicating the general direction of the tone (6 cases). (3) Then imaged pressure or kinaesthesis on the head in the general direction of the tone (5 cases), which (4) becomes intense and definite (5 cases). (5) Finally the auditory perception is terminated by its being referred to the visual schema represented by the pattern for orientation laid out upon the table (6 cases).

B first perceives the tone indefinitely localized (analysis of 6 complete accounts). This phase is followed immediately by some portion of the schema for orientation laid out upon the table and by the eye-kinaesthesis involved in following the visual image of the tone along the schema (all cases). The image, as finally placed, was always a visual image with an auditory core, varying from time to time in hue, tint, clearness, and extent. The final judgment consists in the visualization of the number of the schema, which gives to the tonal image its local context (all cases).

C reports a non-focal visual schema of an arc before him extending on both sides of the median plane just preceding a fairly intensive auditory sensation (analysis of 6 reports). The latter is accompanied by the accrual of a more or less clear visual localizing context to the auditory core. The context consists of an area of the visual schema which gives the general direction of the tone (5 cases). This visual area rapidly narrows down to a clear spot (5 cases) with a definite position in the visual schema. Accurate determination of its position is given in visual directional lines that extend from the spot to the head (3 cases, implied in others). Judgment follows automatically in terms of this visual context. The more lateral localizations (all cases) are accompanied by slight strains of eye-muscles ('effort').

The fore-period for *D* contains a clear visual schema of the table pattern (analysis of 8 cases), with the most lateral portions added eye-kinaesthesis (7 cases). With the presentation of the stimulus the tone is experienced immediately as a spherical visual image (5 cases) which almost instantaneously assumes definiteness in form and position with reference to the visual schema present. Twice when the tone was weak the image seemed to appear only in auditory terms. Accompanying the image is eye-kinaesthesis of focussing on the image (5 cases). The judgment follows at once as the vocimotor image of the number at that particular point of the visual schema to which the image is attached (5 cases). Double images, one at each side, may be accompanied by intensive kinaesthetic imagery of the eyes as of sweeping the visual schema from side to side (2 cases).

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[35] *Op. cit.*, 322.

Two general plans for localizing are thus shown in the introspections. The *O* may first obtain the tone and then apply its image to the visual schema as seen or imaged, or he may visualize the table pattern and see where the tonal image (auditory or visual) makes its appearance on the pattern. The first plan is more generally used, at least in the early stages of practice.

Rough approximations of direction occur usually in terms of eye-movement or eye-kinaesthesis with a given portion of the visual schema in the general direction of the tone standing out more prominently than the rest. Accuracy in direction is obtained when the visual or auditory image becomes attached to the table pattern or the visual schema.

The *Os* show a tendency to close the eyes while localizing, because the principal avenue of distraction is thus shut off, and also because the visual process (most *Os* tend to visualize the acoustic image) becomes clearer when the eyes are closed. *A*, who consistently keeps her eyes open, does not visualize the sound, but experiences it as an imaged pressure or kinaesthesis at a point on the head corresponding with the direction of the sound. Other *Os* at various times have had the same experience.

The visual context of the tone corresponds roughly with its auditory core in its sensory attributes. For example, a weak but clear tone is represented by a small clear visual image and a strong clear tone by a larger image also clear. An unclear tone, weak or strong, calls forth unclear and scrappy visual images.

Double Images at the Critical Phase-Difference of 180°

An interesting phenomenon is the disappearance of the acoustic image at one side and the subsequent appearance of a similar image at the other side, when the phase-difference of the tone at the ears is 180°. It has been suggested that these images are one and the same and that the image must therefore cross through the *O*'s head or behind it.[36]

Good conditions for studying this problem are afforded by this apparatus. The glass slide-tube was moved very slowly from the position 100 to 33 or reverse, changing the phase at the ears gradually so as to insure careful observation at the critical positions preceding, at, and following 180° difference of phase. When the *O* desired, a particular phase-difference was maintained and studied at length. The general results for the four *Os* follow.

A observed two auditory images, one at each side of her head, one less intense at first than the other. They differed in quality and were "two different images." Next "kinaesthesis swept rhythmically from one ear to the other and reversed" its direction. At one time she stated, with an image at the right, "I became conscious of something at my left but on looking there could find nothing. Then for a short time I was unable to tell on which side I was hearing the image, when suddenly it was at my left." Observing later under the suggestion that the image crosses the head, *A* stated that there was a rapid movement of the auditory image across the

[36]Stewart, Phase Relations in the Acoustic Shadow of a Rigid Sphere, *Phys. Rev.*, N. S., 1914, 4, 252; Theory of Binaural Beats, *ibid.*, 1917, 9, 518.

Rayleigh, On Our Perception of Sound Direction, *Phil. Mag.* (6 ser.), 1907, 13, 230.

head during which it "lacked intensity." The image "joined" the *other one.*

B at 180° difference of phase could not localize the image, or else a shifting kinaesthetic attention gave both left and right as correct localizations, or else the sound appeared always to escape to some other place than that which he was fixating. In trying to solve the dilemma he sought at times to place the sound inside his head, but "the localization was equivocal, since it was central and thus at no angle." At other times "the tone at one side would lose its auditory core and leave only the shell of the visual image. Then immediately I realized that the sound was at the other side of my head."

C in all cases imaged the sound at one side as a "large bright spot." There followed "rapid shifts of visual imagery" to the other side of the head "where a second image was also seen." Usually when the image reached the aural axis on one side, "another image appeared concomitantly at the other side. When the two images were equally clear the intensity was greatest. Finally the tone at the first side lost its intensity and its image gradually disappeared." *C* remarked every time that "the images were two distinct images and had nothing to do with each other."

D stated that when one auditory image reached the aural axis at one side it began to gain in intensity, while the sound, now clearly exterior, seemed to "surge into" the ear with the visual context dropping out. Then a slight kinaesthesis in the other ear caused him to look at that side, where he became aware of a "second auditory image weak at first but gradually waxing stronger until both images were of equal intensity. At this point both tones were exterior and surging into the ear. Besides they were diffuse, scatteringly intense, voluminous and unlocalizable except that one was all 'left' and the other all 'right.' Finally the first auditory image weakened and disappeared and only the second image remained, and the visual context began to accrue to it. Kinaesthesis of eye-movement and turning of the head with shifting visual imagery occurred during this entire procedure." At another time *D* stated that "one image originated at one ear, and the other passed away. The sound did not move from ear to ear. It simply accumulated in the images."

When the change of phase at the ears is accomplished *rapidly* an illusory movement of the sound image from one side to the other of the head at 180° phase-difference is evident. This illusory movement is given by the comparatively rapid changes in differences of intensity at the ears and not to a movement of the image itself. It appears to be similar in nature to stroboscopic visual movement.[37]

The evidence points to a rejection of the view that the image crosses through the head or behind it during the period preceding and following 180° difference of phase. It is clear that at 0° difference of phase the image is in the median plane, but no one has ever clearly imaged it in the median plane at 180°. Neither has any one clearly described how it crosses the head at this point. The illusion of movement with rapid changes of phase at this point is, however, decided. The fact that two distinct images may be observed for frequencies of 700 d. v. and above supports the conclusion that the image does not cross the head at 180°. When one of these images moves toward the median

[37]Peterson, *op. cit.*, 350.

plane, the second usually moves a short distance toward the aural axis, and, becoming weaker, finally disappears.[38]

Pseudo-median Localizations

B often reported localizations at 180° difference of phase as median. (See Fig. 1.) He explained, however, that the image was not median in the sense of being localized in the median plane, as is the case at 0° difference of phase, but that the sound was "central" or "at no angle" or "all around" or "equivocal." All the *O*s have experienced a "balancing of the sound," the having of the double sound of equal intensity at the two ears. *B*'s reporting this localization as median simply means that under an instruction for making a single localization he compromised the double localization as median. This is a common error which the writer has noticed for years. See p. 186.

Summary

1. The primary psychological factors which enter into the localization of a tone with closed ears, when the phase relations are altered, are (1) a visual, auditory, kinaesthetic, or tactual image of the tone or a combination of these, and (2) a visual or visualized schema of reference, in this case the 'arc-pattern.' The image varies in clearness, extent, and intensity depending upon its position, the intensity of the tonal core and the modality of the image. The 'arc-pattern' varies in clearness and extent with the different observers.

2. The fundamental psychological criteria for the formulation of judgments of position are: eye-movement or eye-kinaesthesis in the general direction of the sound, giving the rough meaning of 'right', 'left', or 'front', followed by adjustments of eye-movement or kinaesthesis in fixating the tonal image with reference to the visual arc-pattern.

3. Lateral localizations are more difficult than frontal because of (1) general inaccuracy in judgments of direction in indirect vision, (2) the diffuseness of the lateral tonal image, and (3) the apparent vacillating character of these images.

4. The tonal image as laterally perceived appears to be auditorily more intense, voluminous and diffuse than when frontally perceived. There is a tendency, allied to its diffuseness, for the visual context entirely to disappear in lateral localization.

5. When the phase-difference at the ears approaches 180°, the tonal image attains its most lateral position and gradually disappears. It is succeeded by a second image at the other side of the head when the difference in phase is again less than 180° and the phase at the latter side is leading. In the intermediate

[38]Hartley says that when "the image has reached a position near 90°, its direction remains unchanged, but in spite of equal intensity, it moves in toward the ear.... Beyond this point there is no corresponding position for an actual source and hence the curves tell us nothing as to where an image is to be expected;" *op. cit.*, 377.

critical position double images, one at each side of the head, may be observed. When phase alters rapidly through this critical position, the rapid succession of images may produce an illusion of movement of a single image through the head or behind it.

6. Observers may, under instructions to make single localizations, compromise a double lateral localization by reporting a median localization.

Binaural Localization of a Tonal Complex by Open Ears: Variation in Position of Dual Source of Sound

Wave-phase may be studied without the use of conductors to the ears. An account of the method and a description of the phenomena involved, as obtained by C. E. Seashore and the writer in 1918 at the State University of Iowa, are being published.[39]

The apparatus then used consisted of two telephone receivers connected in parallel from the same sound-source, with a two-meter stick suspended between them. The receivers were energized so as to produce a tone of 680 d. v. It was found that the *O*, by closing one ear and moving his head carefully from one source to the other with the side of his head parallel to the axis of the receivers, experienced a series of intensive maxima and mimima, which correspond exactly with the points of reenforcement and interference that obtain in the stationary wave set up between the two receivers.

When the *O* with both ears open (the aural axis parallel to the axis of the receivers) moves slowly from one receiver to the other, he localizes the tone in the median plane once for every one-half wave-length that he advances. These points of median localization correspond with the loop centers of the stationary wave.

Midway between the loop centers are the nodes. They are *critical* regions for localization. When the head is moved from a node toward a loop the image of the sound travels in the same direction as the head, but faster, toward the median plane from a position at the side from which the head is moving. The image reaches the median plane when the center of the head reaches a loop center. If the movement of the head is continued, the image then passes on out of the median plane in advance of the head until the next node is reached, when the image lies at the side toward which the head is advancing. Thus, if the head moves from left to right in passing from one node to the next, the image also moves from left to right, starting at the left side, swinging about the head, and ending at the right side. If now the head moves on from this second node to a third node, the image again moves from the left to the right as before.

We may summarize the situation for open-air localization as follows:

1. The space between the receivers may be thought of as divided into unit localization regions, each measuring one-half the wave-length of the tone and every one an exact counterpart of every other.
2. Median and balanced localizations occur alternately for each one-quarter wave-length of the tone used.
3. The movements of the image are experienced, not only in the line of the receivers, but practically anywhere within the range of audibility. These changes in other regions are not everywhere uniform, but at present no definite statement can be made as to their law.

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[39] H. M. Halverson, *Univ. Iowa Studies in Psych.*, No. 8, 1921, monograph in press.

4. With low tones the image of the sound sweeps through a longer arc about the head than it does with high tones. At 512 d. v., *e. g.*, the image sweeps from 90° at the left of the median plane to 90° at the right, whereas at about 1500 d. v. the range of movement becomes so limited that the image is confined to the immediate vicinity of the median plane.

We set up the Iowa apparatus at Clark with the intention of repeating the experiment under more careful control and with psychophysical procedure. Instead of allowing the *O* to move his head, we had him bite on a biting-board and moved the two receivers suspended from the measuring-stick back and forth in the aural axis. A pointer on the biting-board indicated on the cm. scale that connected the receivers the position of the receivers relative to the *O*'s head. The apparatus was set at a definite position and the stimulus presented. When the *O* had localized the tone, the stimulus was shut off and the apparatus then set at another position. Stimuli were presented in chance order.

The tone was obtained, as at Iowa, by placing a small electric generator in the telephone circuit and driving it from a tonoscope used as a constant speed motor. In this way we obtained a frequency of 476 d. v. for which at 70° F. the wave-length is 72.4 cm. Two Edison cells were inserted into the field-magnet circuit of the generator to give the tone the desired intensity.

As soon as we started to work we discovered that the tone was not pure and that different upper partials could be distinguished in it. The second partial, 952 d. v., was very prominent, and in the vicinity of either receiver the more musical *O*s could distinguish still another partial. Attempts to secure purity of tone were unsuccessful, as is apt to be the case in work with telephone receivers.[40] It occurred to us, however, that it would be profitable to study the joint localization of the two more prominent partials, and see whether they operated independently, each in accordance with the law that we had verified at Iowa. Two of our more musical *O*s were able consistently to distinguish two partials, to identify them on a qualitative basis, and to make separate localizations of them. The other two *O*s were less ready at analysis and frequently localized only what appears to have been the more prominent partial. Since the intensity of a tone varies with its localization, that is to say, with the phase-relation of its stimulus, it was to be expected that in these cases sometimes one partial and sometimes the other would be predominant. Moreover, when the two partials lie at approximately the same angle, analysis is comparatively difficult, and the tendency to make a single localization is thus increased.

Ideally we should expect to find the course of each of the two images following the law already laid down. When the receivers are moved continuously with respect to the head, we should expect the two images to pass around the head through the median plane in the direction opposite to the motion of the receivers, and the image of the second partial to complete its cycle twice as often as the image of the first partial.

Except for Baley's dichotic experiments[41] the only instance of localizing with partials, as far as we know, is reported by Thompson[42] who caused the tones of two forks, 256 d. v. and 512 d. v., to be conducted by tubes to the ears so that in the first case the tonal complex was localized in the ears. Then, by causing the 512 d. v. tone to enter the ears in opposite phases, he obtained the higher tone localized at the back of the head while the lower remained localized in the ears.

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[40]*Cf.*, *e. g.*, D. C. Miller, *Science of Musical Sounds*, 1916, 148 ff.

[41]S. Baley, *op. cit.*

[42]S. P. Thompson, Phenomena of Binaural Audition, II, *Phil. Mag.* (5 ser.), 1878, 6, 383.

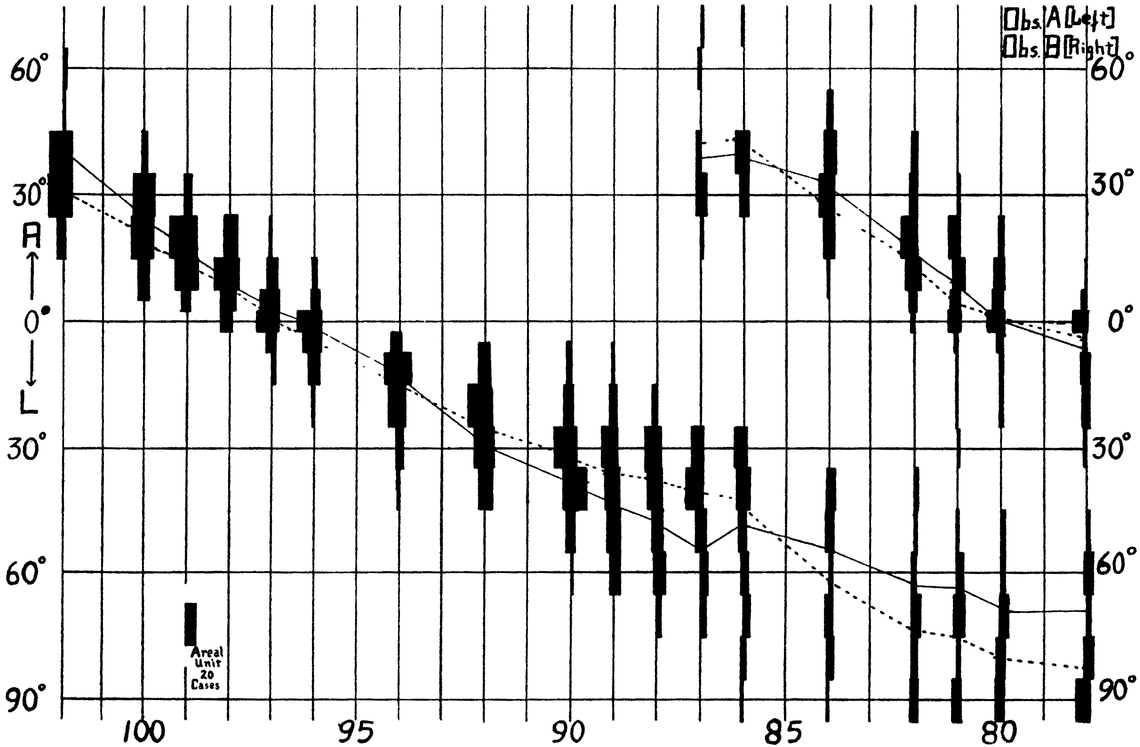

Fig. 2. Open ear localization. Graph showing distribution of frequencies of localizations in degrees right and left of the median plane for positions indicated on the abscissa (cm.). Abscissa values are in terms of the scale of the apparatus for localization with open ears (see text), and represent the position of the O's head between the two sources of tone. Localizations by A (dotted line) and B (solid line) are indicated to the left and right of the ordinates respectively.

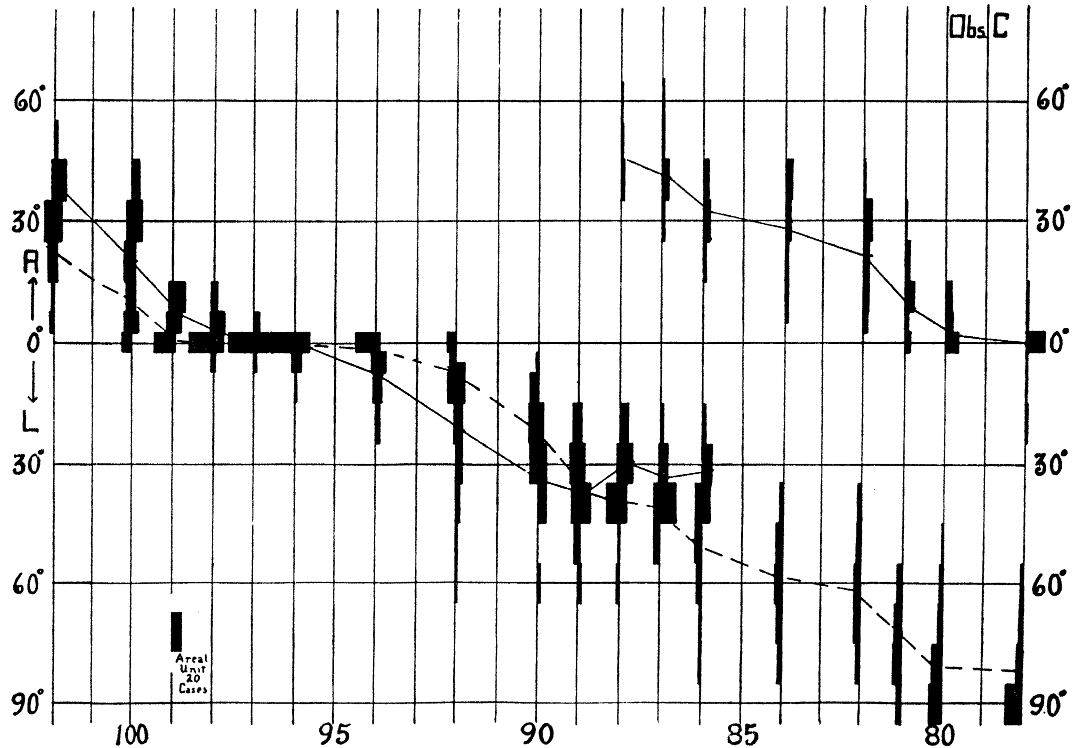

Fig. 3. Open ear localization. Graph showing distribution of frequencies of localizations in degrees right and left of the median plane for positions indicated on the abscissa (cm.). Abscissa values are in terms of the scale of the apparatus for localization with open ears (see text), and represent the position of the *O*'s head between the two sources of tone. Localizations by *C* for the 476 d. v. (dotted line) and the 952 d. v. (solid line) partials are indicated to the left and right of the ordinates respectively.

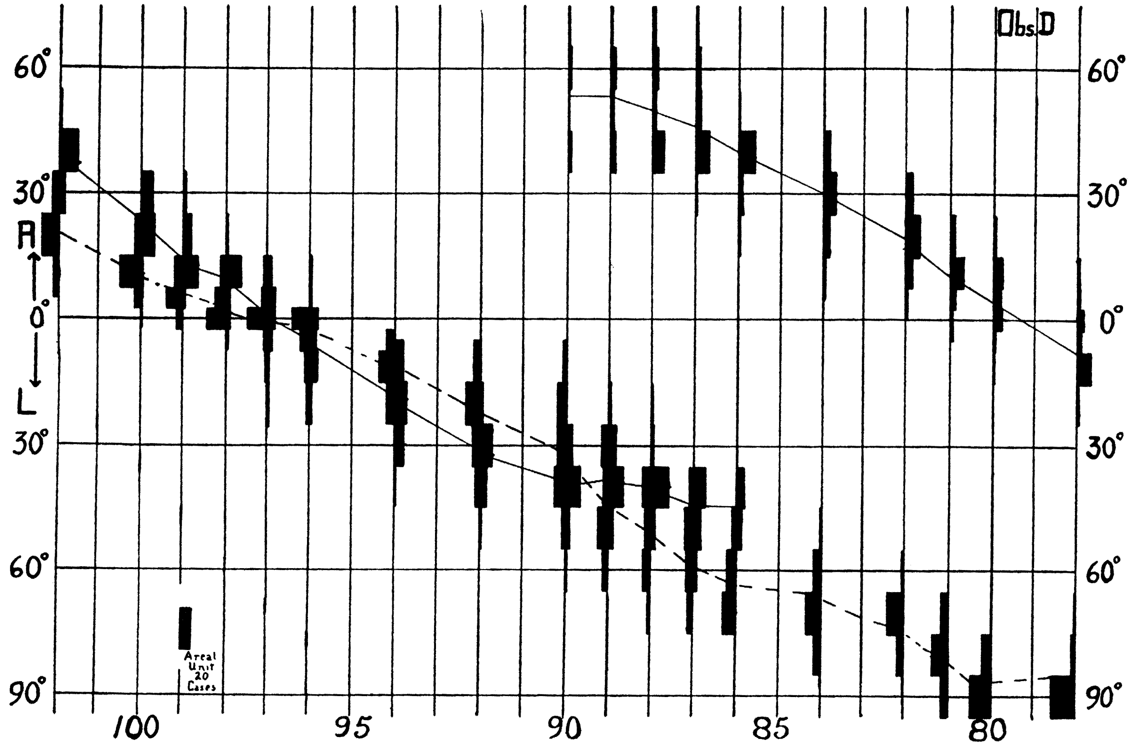

Fig. 4. Open ear localization. Graph showing distribution of frequencies of localizations in degrees right and left of the median plane for positions indicated on the abscissa (cm.). Abscissa values are in terms of the scale of the apparatus for localization with open ears (see text), and represent the position of the *O*'s head between the two sources of tone. Localizations by *D* for the 476 d. v. and the 952 d. v. partials are indicated to the left and right of the ordinates respectively.

Results

Graphical Presentation

The graphs of Figs. 2-4 were compiled from the results of four *O*s. Localizations were made in terms of degrees right or left of the median plane of the *O*. 'Zero' is any position in the median plane and 'left 90' and 'right 90' are in the aural axis at the left and right respectively. The graph of *O*s *A* and *B* shows the distribution of frequencies in localization in degrees at various positions (cm.) of the sound-sources with respect to the *O*'s head. *A*'s histograms lie on the left side of the vertical lines and *B*'s on the right.

The horizontal line [0°- 0°] represents the median plane of the *O*'s head. Right and left of the median plane are indicated respectively above and below this line. Numbers on the abscissa scale give the positions (cm.) at which the apparatus is brought at rest for purposes of localization.

Each of the ordinates, bearing a histogram, is a graphical representation of the *O*'s localizations at that position for the apparatus. The form of presentation is analogous to that for Fig. 1. Where two separated histograms appear on the same side of an ordinate (see positions 78 to 87), the situation is as follows: (a) either the *O* gave a double localization when the stimulus was presented (frequent occurrence), or (b) he gave one localization at one time and the other at another time under like conditions of observation. Occasionally double localizations were reported at 80 and 89, but these were so infrequent that the graphs fail to show them.

C and *D*, who were more musical *O*s than *B* at least, were better able to analyze the tonal complex into its primary components than were *A* and *B*. Their results are shown in Figs. 3 and 4, where the histogram on the left represents the frequency of localizations of the first partial and the histogram on the right the frequency of localizations of the second partial. It will be seen that both *O*s made double localizations for every presentation of the stimulus and in a great many cases triple localizations (see positions 78 to 88). For example, a typical observation of *C* or *D* at position 86 would be: Upper partial at 'right 40', same upper partial at 'left 40', lower partial at 'left 50'.

The graphs reveal in general that, for positions ranging from 102 to 98, localizations are made to the right of the median plane; from 96 to 88, to the left; and from about 88 to 78, both to the right and to the left. The images cross the median plane at two positions (97 and 80 approximately). The distance between these positions, 17 cm., is one-half wave-length of the upper partial. The course of the more prominent image (the upper partial) is very much the same for all *O*s from 102 to 88, and again from 87 on the right to 78.

Localizations near the median plane are less scattered than at the extreme lateral positions, a fact that corresponds with the assertion of the *O*s that lateral localizations are less definite.[43]

A and *B* never failed to localize the image of the upper partial. In the critical region (87-84) they generally reported two images of the upper partial, one at each side; and from 82 to 78 they often reported an image at the right which was recognized as this upper partial and another at the left which they could not always successfully identify; sometimes they were sure that it was the lower partial and at other times they were unable to distinguish it from the image of the upper partial at the right.

[43] *Cf.* Bowlker, *op. cit.*, 322.

B's localizations are somewhat more to the right of those of the other *O*s (Fig. 2). Other *O*s often reported localizations as far left as 90° at position 78, but *B* seldom reported anything to the left of 70°. Rarely, however, he reported localizations to the right as extreme as 90°, a localization that no other *O* ever made. These reports occurred at positions 102, 89, and 88, but are too few to show in the graph.

The graph for *C* shows that images of both upper and lower partials are reported at each position of the apparatus. From position 102 to 89 both are reported regularly and are introspectively spoken of as "very adjacent" (*cf.* Fig. 3). At 102, 100, 92, and 90, where the images appear to be more definitely separated, the separateness is undoubtedly exaggerated. The images are reported as very close spatially; the anxiety of the *O* to set them apart as two distinct images seems to have caused him artificially to indicate a distance between them. For example, *C* often remarked that in localizing one image, he was also localizing the other as they were in the same lateral position, and yet he stated different localizations for them because of his total impression of their independence. In this region *A* and *B* (Fig. 2) failed utterly to distinguish two images; presumably they localized the two as one. Their failure to distinguish the images accounts for the greater variation of their localizations in this particular region. The images here are very close together and move in the same direction at about the same speed (as other observations show), and this similarity serves to make their perception only the more difficult.

From position 88 to 86 *C* generally reported three images, the upper partial at his right, the upper partial again at his left, and the lower partial at his left (Fig. 3). From 84 to 78 *C* reported always two images, the upper partial at his right and the lower partial at his left.

A feature of *C*'s observations is his tendency to localize toward the median plane. From 99 to 94 and from 80 to 78 the position of the images is predominantly medial. *C*'s introspective reports show that the images in passing from one side of the median plane to the other are localized high above his head, whereas the other *O*s localize the images at points in front of them. It appears thus that for the region considered a given angular change in the position of the image in the horizontal plane of the ears is observed as a somewhat greater arc than a similar angular change in the region of the zenith. *D*, who can at will place the image in front, behind, or overhead, stated that distances above 'seem less' than the same distances in front or behind. He also reported that the distance of the arc 60°-90° left or right is less when observed in the horizontal plane than when observed in the vertical plane of the ears.

D's graph (Fig. 4) is essentially the same as *C*'s. *D*, however, reported more triple localizations than *C* and showed no tendency to localize toward the median plane.

C's and *D*'s graphs show clearly how the images of both the upper and lower partials pass from the right of the median plane to the left. They also show that the image of the lower partial proceeded down to the region of 90, left. The formal experimentation stopped at this point, but incidental investigation showed that for positions beyond 78 this image gradually fades out while another similar to it appears at 90° right and moves toward the median plane. If the image is followed through and beyond the limit at the other end of the graph (102) the same movement is observed in reverse order. When the image of the upper partial has reached a point of about 45° left, it appears in most cases to be "fixed" there, that is to say, it does not move farther to the left as we should expect when the apparatus is moved. Remaining at this place it gets weaker and weaker and finally disappears (at the point where the image of the lower partial is most prominent). Occasionally *C* and *D* reported that the image of the upper partial moved with the image of the lower until it reached a point near 'left 90' when it disappears leaving only the lower partial audible on that side.

C and *D*, under instructions to report what takes place at the angle of 'balanced localization' while the apparatus is being moved, state that the diminution in the intensity and clearness of one image is accompanied by a simultaneous increase of the intensity and clearness of the other image. While the *O* is attending to the very clear image at the left, he finds, as this critical region of localization is approached, that a similar image, of weak intensity and not very clear at first, is claiming attention. Then as the apparatus is moved further along, a position (point of balanced localization) is reached where both images are of equal intensity and clearness; then a point where the second image surpasses the first in intensity and clearness; and finally a stage where the *O* perceives only the second image. The quantitative data (Table I) for these *O*s show clearly this phenomenon.

Bowlker, the first to report multiple images, calls the angle which this appearing image forms with the median plane of the head the "cross-over angle.[44]" This usage, it appears to the writer, is misleading, inasmuch as the image does not cross over from one side to the other. The angle may be called the "angle of balanced localization" and is thus referred to hereinafter by the writer.

From Hartley's calculations[45] for the location of the sound as a function of difference of phase, an angular displacement of the image of 90° right

TABLE I

Number of right and left localizations reported for image of upper partial at various positions indicated. Observers *C* and *D*.

Position of apparatus with respect to observer's head (cm.)	Observer *C* Left Image	Observer *C* Right Image	Observer *D* Left Image	Observer *D* Right Image
90	54	2	54	27
89	54	9	54	39
88	54	14	52	54
87	50	26	42	52
86	46	34	30	52
84	15	50	10	54

or left of the median plane for a tone of approximately 650 d. v. should occur for a phase-difference of 180°. For tones of somewhat higher frequency, two images should appear whenever the angular distance of an image is slightly less than 90° from the median plane.

Experimentally this conclusion is verified. The image of a tone of 680 d. v. does not attain an angular displacement of 90° before a similar image appears upon the opposite side of the *O*'s head. In fact at this frequency it is just barely possible to make out the two images simultaneously for a very limited portion of the total cycle of phase-differences.

In our work with a 930 d. v. tone double images appeared very distinctly when the *O*'s head was at the point of balanced localization (a quarter wave-length from the point of median localization). Here it was possible to move the head for a small distance either left or right without either of the images disappearing. Hartley's mathematical plot of the direction of the images of a 930 d. v. tone indicates that the angular distance separating the two images should be 102° when both are equally distant from the median plane (p. 381). In the same way he shows that three images, each separated from its neighbor by approximately 50°, should be observed for a tone of 1860 d. v. when one of the images is in the vicinity of the

[44] *Op. cit.*, 323.

[45] *Op. cit.*

TABLE II

Tabular analysis of description of auditory sensations and the corresponding visual images that occur in the simultaneous localization of two partials of a tonal complex under experimental conditions (see text) of localization with open ears. Numbers in parentheses are numbers of instances in which a positive report occurs in the protocols.

	Auditory Image		Visual Image	
Obs.	Upper partial	Lower partial	Upper partial	Lower partial
A	Clear (8), intense (8), thin (3), bright (2), high (10), rough (1), noisy (1), weak (1), unpleasant (2), definite position (5), lacks volume (1).	Clear (3), not clear (2), not definite or intense (2), low (6), varies in clearness (2), ear-kinaesthesis (3), round (1), full (1), voluminous (4).	Clear (2), definite (3), round (2), luminous (1), white spot with black center (1), black spot with yellow halo (7) shading off into grey (1).	Smooth (1), grey (1), and pear-shaped spot (1). Has yellow halo (1), indistinct (2).
B	High pitch (4) of stronger intensity at median plane than at lateral position (1).	Low pitch (4), ear-kinaesthesis accompanies tone (1), unstable (1).	Small (3), a spot (8), definite (5), grey (1), yellow (5), a fuzzy white ball (2) sometimes within a light mist (1).	Clear (2), not clear (2), faint grey spot (2), dark blue spot (4), black (1), just dark (1).
C	Piercing (4), intense (5), hard (6), rough (2), metallic (4), not pure (2), penetrating (7), complex (1), high pitch (18), of oboe or reed timbre (3).	Smooth (6), soft (5), intense (2), not intense (4), diffuse (7), low tone (18), like pure tone of tuning fork (6), more distant than upper partial (9).	Small (4), spherical (9), clear (11) and intense (5), hard (5), bright (4), luminous (3), extensive (1), nearer head than other image always.	Clear (3), not clear (4), small (1), large (3), smooth (1), round (1), oily (1), grey hue (3), dark (1), distant (9).
D	Sharp (9), intense (6), not intense (3), hard (1), definite and clear (11), sparkling (2), unpleasant, (2), impure (2), small (11), high pitch (10).	Soft (7), smooth (4), diffuse (2), extensive (2), thin (1), pure (1), clear (2), definite (1), intensive (2), humming (2), low tone (10), distant (11), fading (2).	Clear (9), intense (6), small (6), spherical (3), definite (8), depthy (2), bright (13), yellow spot (9) with grey halo (3). Like singing flame (1).	Soft (2), extensive (7), unclear (3), thin (3), bluish grey (7), very distant (3), larger than image of upper partial(4).

median plane. Bowlker[46] actually observed three such images with tones of 1675 d. v. and 2090 d. v. At 2310 d. v. he experienced difficulty although the images were present; and at 3050 d. v. he found localization practically impossible. We may therefore say of pure tones that, when the difference of phase at which the tone arrives at the ears is less than a half wave-length, two images are observable, and, when the difference of phase is decreased, a point is reached where it may be possible to observe three images.

Introspective Analysis

Limits of space[47] prevent an even partially complete presentation of the introspective data. The following accounts are of value as general indicators of the nature of the localizing process.

The description implies frequently the ability of the *O*s to distinguish between the two partials. Such distinctions were made by the *O*s partly in terms of the auditory core of the perception and partly in terms of the visual localizing context. Table II summarizes various attributes upon which these distinctions were based, and also throws light upon the qualitative nature and complexity of the perceptions involved.

Observer A begins always with (1) the focal auditory perception of the tone. (2) There follows a period of search, characterized by the kinaesthesis of eye-movement as the visual field is swept. There is a clear visual image of the schema of reference with some of the numbers representing localizations, upon it, and later the visualization of the tone upon the schema. Two tones may be thus simultaneously localized. So far, however, the localization is indefinite. (3) Then comes a rough stabilization of the image in terms of kinaesthesis within the head, giving roughly the direction of the tone; and (4) then the image is localized more accurately by placing it in visual terms upon the visual schema of reference, or rarely by placing the schema upon the tonal image.

Observer B gets (1) first an auditory perception of the tone, which is usually associated with a visualization of a portion of the arc of the schema of localization. (2) Immediately the tone is visualized clearly with definite qualitative characteristics. (3) Then comes a period of adjustment of the visualized tone to the visual schema of localization. Many numbers upon the schema may be clear at first, and drop off as the localization narrows down to a smaller region. The localization finally consists in the reduction of the visualization to the region of a single number. When there is a sudden shift in this localization accompanied by a change in the auditory quality of the core, *B* reports that he is aware of a second partial. (4) There is for *B* a characteristic process of searching, which may precede the localization just described, or may follow it as a verification. *B* sweeps the visual arc with his eyes (in imagery) until he detects the faint image of a tone, then scrutinizes this region to see if the visual image of the tone will become distinct and clear. If it does, he has still to "attach" the image to the schema by the process described above. (5) The process continues indefinitely by way of localizations and verifications, and ends with a verification. It is worth especial mention that, in cases of 'balanced local-

[46] *Op. cit.*, 324-326.

[47] *Cf.* footnote 1. The reader will have to accept the validity of the writer's generalizations or consult the bound manuscript in the Clark University Library.

zation,' *B* definitely reports a double localization (at the two sides) in the presence of a single auditory quality.

Observer C (1) begins always with an auditory perception of the tone, which is not focal, and a visual image of the arc of localization above the head, which is obscure. (2) Then the arc becomes distinct, the tone becomes focal, and a visual image representing the tone, is added to the auditory core. (3) Frequently this process of clarification is then reversed, and the tonal perception is replaced by the eye-kinaesthesis of searching, an occurrence which means that *C*, having localized the first partial, is now seeking the second. (4) The second partial is next localized in the same manner as the first. (5) Finally both partials are localized together. In this final stage, the two images may be focal simultaneously, or attention may shift repeatedly back and forth from the one to the other. The visualized arc at this stage is apt to become obscure, although *C* experiences no difficulty in making the verbal report of the two localizations.

Observer D (1) in all cases enters upon a localization with a visual image of the arc-path, extending from one side of the head to the other with its ends in the aural axis and making an angle in front about 50° above the horizontal plane. *D* does not, however, visualize the specific position of the schema of reference upon this arc-path. From this point on the process of localization varies with the position of the images.

(*a*) When the lower partial is near the aural axis and the upper partial near the median plane, then (2*a*) the upper partial is localized first, immediately and definitely. The localization is in verbal terms and is not mediated by visual imagery of the schema of reference. (3*a*) Then there is a vague awareness of the lower partial, which is at first located roughly by the eye-kinaesthesis, and (4*a*) is then definitely visualized and localized after the manner of the upper partial. (5*a*) In the final stage *D* verifies his tentative localizations by repeating the process just described.

(*b*) When the upper partial is in the position of 'balanced localization' and is therefore double, (2*b*) the two images of the upper partial appear immediately and simultaneously, and are of like appearance. *D* looks back and forth in imagery from one to the other. (3*b*) Then there is a period of search for the image of the lower partial, which ordinarily appears as faint, indistinct, and diffuse, and sometimes overlaps one of the images of the upper partial. (4*b*) Next the images of the upper partial are applied simultaneously to the visual schema, and (5*b*) then the image of the lower partial. (6*b*) The process concludes with a period of verification as in (5*a*) above.

(*c*) When the images of both partials are both near the median plane, (2*c*) the image of the upper partial is still first placed definitely within the visual schema, and (3*c*) the image of the lower partial, less distinct, is subsequently established. The remainder of the process of localization follows along as in the two cases already described, ending in a period of verification.

Summary

1. Two tones, separated by an octave, were reported by all four observers. Two observers were able to localize each tone of this pair independently of the other at every presentation of the stimulus. The other two observers were able to make this separate localization only at times. *See Figs.* 2, 3, 4.

2. The localizing context for all observers consisted usually in the visual image of a spot, approximately spherical, fixed in a spatial schema at a point from which the tone appeared to issue. This spot varied in clearness, hue, size, distance and other characteristics from time to time.

3. The distance from median localization to 'balanced localization' for the lower tone was approximately twice as great as the corresponding distance for the higher tone. This result is what would occur if the two tones follow independently the law of phase. *See Figs.* 2, 3, 4. For example, the distance that the receivers had to be moved to shift the image of the higher tone from the median plane to the position of 'balanced localization' was found experimentally to be 8.7 cm. This distance should correspond to a quarter of the wave-length of the second partial of 476 d. v., which at 70° F. is 9.0 cm.

4. The image of the second partial is ordinarily visualized as nearer to the observer than the image of the first partial. It is smaller and more distinctly outlined.

5. The image of the first partial shifts through a complete semicircle from 90° to the left of the median plane to 90° to the right of the median plane. The image of the second partial, however, shifts only through an arc of about 90° from 45° to the left to 45° to the right. For it the position of 'balanced localization' is thus at 45° left and right, not at 90°. *See Figs.* 3, 4. This result accords with other investigations which have indicated that with tones of higher pitch the angular range is limited and that the position of 'balanced localization' (the limiting position of movement of the image) is much less than 90° from the median plane.

6. The course of the image in passing through 180° difference of phase (point of 'balanced localization') is discontinuous. The image is either at one side of the observer or the other, or there are simultaneously images at both sides; there is no intermediate localization for the image.

The observers occasionally had the illusion of the movement of the image from one side to the other of the head when the receivers were moved at the critical position of 'balanced localization'. When, however, the stimulus was not moved and the observers were asked to describe the localization at this setting, they usually reported double images, *i. e.*, a reference of the tone to both sides simultaneously. It seems that the tone in this critical position is not ordinarily referred to a single point within the head, but that such a reference comes about only as a result of the tendency of observers to compromise a double localization under an instruction for making a single localization. See pp. 187, 195.

7. When the two images lie together in the region of the median plane it is extremely difficult to distinguish between them, and the observer tends to report a single localization of a tone of different timbre from either of the partials when they are localized separately.

8. The average consistency of localization was greater for the observers who habitually distinguished between the two partials. The average mean variation for these observers is 6.35°. The average mean variation for the other two observers is 10.3°.

BINAURAL LOCALIZATION OF A TONE BY OPEN EARS: VARIATION OF RELATIVE INTENSITY OF TWO SOURCES OF SOUND

The fundamental problem of auditory localization is the essential condition of localization. Localization may be due to the difference of phase of the tones as they enter the two ears, to the relative intensities (binaural ratio) of the two tones as they enter the two ears, or to the difference in time at which impulses reach the ear drum (Klemm)[48]. The pendulum seems to be swinging toward difference in phase as the primary condition of localization, although the extent to which other factors contribute is not yet definitely made out. It is not impossible to see how phase-difference might be reducible to time-difference, and the last two theories harmonized. It was the purpose of these experiments to discover to what extent intensive differences co-operate in localization.

Our own experiments with the closed tubes favor a theory of phase-difference,[49] and it seems furthermore that phase-difference is also important in the localizations with open ears.[50] It is plain, however, that differences of intensity may exist at the two ears in open-ear localization, because of the existence of the standing wave with the two ears simultaneously at different regions of it. The actual relations of the intensities at the two ears depend on the relation of the width of the head to the wave-length of the tone. The image is, however, consistently referred to the side at which phase is leading, and this rule holds in many cases in spite of the fact that under it the image is referred toward the side where the intensity of the standing wave is weaker. In a sense, then, the localization may follow a rule of phase-difference even when the rule operates in opposition to the rule of intensive difference.

In incidental observation at Iowa and at Clark, the writer has frequently observed that a very great variation in the relative intensity of the two sources of sound in open-air localization (variation in electric current to the two receivers or in nearness of the receivers to the ears) does not seem to result

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[48]See p. 180.

[49]See pp. 187-188.

[50]See pp. 198-200, and the writer's experiments at the University of Iowa, *op. cit.*, monograph in press.

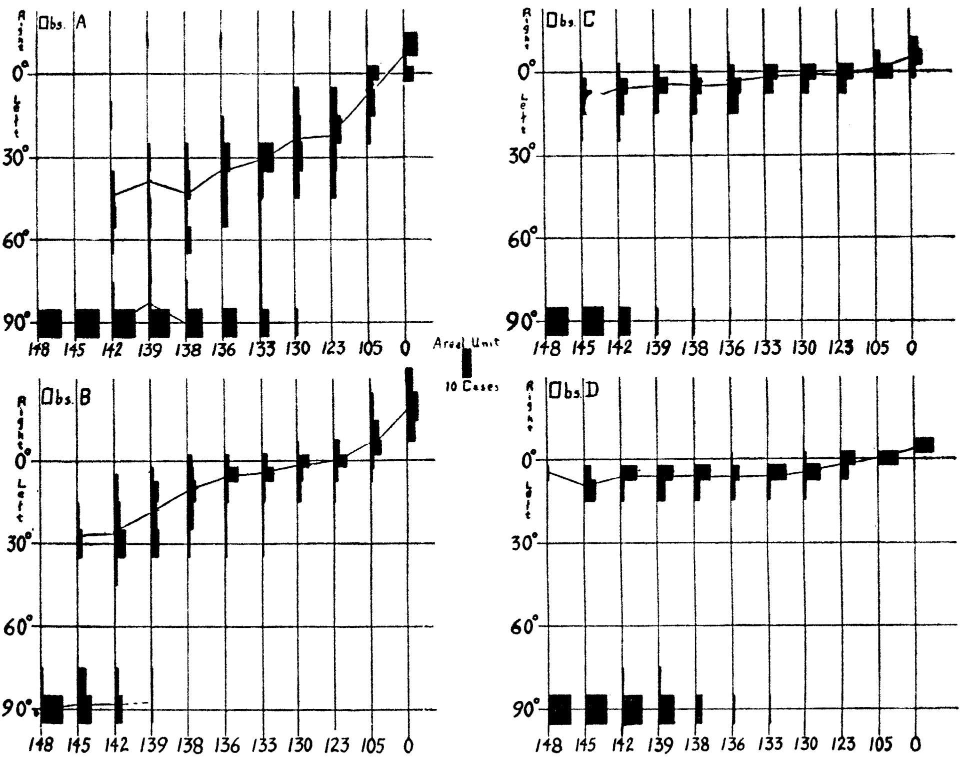

Fig. 5. Open ear localization. Graphs of four *Os*, showing distribution of frequencies of localizations in degrees right and left of the median plane for the positions indicated on the abscissa (mm.). Abscissa values are for the scale of the rheostat, and represent, electrically, successive values of the binaural intensive ratio: "0" indicates equal current to the two receivers on either side of the head, and "148" maximal intensity at the left with minimal intensity at the right. The medial and lateral images, distinguished by the observers, are shown separately on each graph.

in a movement of the tonal image as long as the phase-relations of the two sources remain unaltered. In the following experiments he has sought to investigate this matter systematically.

The same apparatus was used as is described in the preceding section of this Study except that the intensity of the sound at the receivers was reduced by removing the two Edison cells from the field-magnet circuit of the generator. The receivers were brought in toward the *O*'s head until they were but one-half wave-length apart. Thus only a few cm. separated the ear from the receivers. By placing the receivers but one-half wave-length apart, the head becomes a prominent barrier to the passage of a tone of this frequency (476 d. v.). There is thus no standing wave to be taken into account.

A slide rheostat with mm. scale (central position, "mm."; each extreme, "152 mm.") was inserted into the circuit of the receivers with each receiver in parallel with one side of the resistance. A shift of the slide therefore decreased the current through one receiver and increased it through the other, resulting in corresponding alterations in the intensity of the sound. At the extreme position of the slide one receiver was short-circuited and the other, in parallel with the entire resistance, maximally energized. In the experiments herein recorded the extreme ends of the rheostat were not resorted to since the receiver ceased to be effective as stimulus before short-circuiting was reached.

The *O* was to localize the sound, using the plan of the previous experiment. The slide was moved to one of the positions of the rheostat indicated in Fig. 5 (mm. scale) and the stimulus presented. After the localization had been reported, the slide was moved to another position and the same procedure followed. The stimuli were presented in the order in which the digits appear in the extension of the numerical value of π ('chance' order).

Series I: *Discrete Variation of Binaural Ratio with Tones in Phase and with Left Tone Always More Intense*

The receivers were connected in phase so that when the intensity at the two sides was equal, the sound was then localized approximately in the median plane. (When the receivers are connected in opposite phase, the localization is at once lateral even though the intensity of the sound is equal, 'balanced localization'.)

Positions on the rheostat were selected so that, with the exception of one position (0 mm.) where the electrical intensities are equal, the intensity of the left sound should always be greater than the right. Under these conditions we should expect localization to favor the left side throughout.

The results for each *O* under these conditions are plotted (Fig. 5) from the results of twenty-five observations at each position. The abscissa values on each graph are the millimetric positions on the rheostat at which the slide was set when the stimulus was presented and the ordinate values are degrees of localization right and left of the median plane. The positions investigated are spaced equally along the abscissa, although the intervals between them represent very different amounts of electrical change. These positions were chosen to give a large

number of points at regions critical for change in localization. The significance of the histograms erected upon the ordinates is the same as for the other charts discussed above.

The graphs are similar. The *O*s agree essentially in changes in localization caused by changes in the relative intensity of the sounds at the receivers. All tend to localize the sound toward the side of the greater intensity although they differ somewhat in the amount of this tendency. With the relative intensity at the ears equal (0 mm.) the localization is for all *O*s a trifle to the right of the median plane; the apparatus was apparently not precisely adjusted for median localization. At 105 mm. on the rheostat the localizations have taken a slight turn toward the left,—not a great difference, however, since the slide of the rheostat is moved 105 mm. out of the total possible distance of 152 mm. For each succeeding move of the slide the localizations show more and more a lateral tendency until a position is reached where, in addition to the image so far attended to, a second image, at first faint and elusive, makes its appearance at the *O*'s extreme left. From here on the first image wanes in clearness and intensity, though very slowly, while the second image waxes correspondingly stronger. [For *A* a point (139) is reached where regions of localizations for the two images overlap, although the images in each separate case remain distinct.] Subsequently (148) the first image disappears and the localization is of the second image alone. In a word, then, as the binaural ratio of intensities operates to favor one side more and more, the image moves toward that side until it reaches a point where it disappears. The point varies with the *O*s (8.0°- 43.3°), but in no case does the image approximate the aural axis of the observer. The illusion of a shift to the aural axis comes about because a second image is substituted in the aural axis for the first which disappears above the axis.

It is important to note the large differences required in the intensity-ratio (as shown by the millimetric distances on the rheostat) to effect small changes in localization. The slide of the rheostat was moved more than two-thirds its entire distance to the left (0-105 mm.: an electrical ratio greater than 5:1) to effect the first small change in localization, while no intensity-ratio was adequate to move this image in question laterally more than 22.1° (av.). The position of the second image was not affected by changes in the intensity-ratios. Some of the *O*s were more sensitive to the presence of this second image than others. The degree of sensitivity of the four *O*s to this image is indicated on the individual graphs by the number of cases in which the second image was reported.

Series II: *Discrete Variation of Binaural Ratio with Tones in Phase Throughout Complete Intensive Range*

This group of experiments differs from the first series in that the binaural ratio of the intensities was varied over the complete

intensive range from an extreme position with the right tone more intense to an extreme position with the left tone more intense. With each *O* 25 localizations were made at each of nine positions. These positions were selected in preliminary experiments so that they would yield data at the more critical regions of change and also so that they would offset the constant error of all *O*s to localize toward the right. The median position gave approximately median localization and the other positions localizations to the right and left respectively.

The results are shown in Table III. In each cell of this table the localization indicated at the right is of the frontal image, and at the left of the lateral image. As we have already seen in Series I, the frontal image never fuses with the lateral, and the two exist together in a certain critical region. For *A* and *B* the frontal image never becomes more lateral than 43° right or left of the median plane; for *C* and *D* it moves scarcely at all, never passing beyond 7° from the median plane. The average of the average mean variation of localization for all *O*s is 4.3°. The course of the frontal image is also shown in Fig. 6.

Series III: *Continuous Variation of Binaural Ratio with Tones in Phase throughout Complete Intensive Range*

The *O*s were now asked to note the changes in localization when, with both receivers sounding, the intensive ratio was varied continuously. The variation was accomplished by presenting one binaural stimulus first and then moving the slide of the rheostat. Two procedures were followed. (1) With the intensity of the two receivers approximately equal, the intensity of one was increased while the intensity of the other (necessarily) decreased. (2) With a difference of intensity between the two receivers, the intensity was varied so as to bring them to approximate equality of intensity. The movement of the slide was made by hand as uniformly as possible, and required, after practice, 35 sec.

The results accord with those obtained in the two preceding series of experiments, with one exception. There is reported by three *O*s a movement (which proved to be illusory) of the image moving from the median plane to the aural axis. When the intensities of the receivers are varied gradually from equality to a point where one completely overwhelms the other, the image moves from a position in the *O*'s median plane to a certain point, not far from the median plane (*cf.* Fig. 5), on the side which intensity favors. Here the image remains fixed, while a second image gradually becoming more intense appears at the same side in the aural axis accompanied by 'an appearance of movement' from the position of the first image to the position of the second.

That this movement does not involve the original image itself is shown by the fact that the latter may be observed in its fixed position after the 'movement' has occurred. The phenomenon is, as it were, a withdrawal of support from the first image in favor of the second. Upon reversing the intensive change the 'movement' recurs in the opposite direction.

The following analyses of reports indicate the nature of this 'movement' for the various *Os*. The numbers in parentheses represent the number of instances reported.

Observer A reported 17 times that in passing from the region of the median plane to the aural axis the sound image "splits up." The passage is not a "simple trip", but very complicated. The image in the region of the median plane first begins to fade. Then another image appears at the aural axis and soon becomes clear. While the image at the median plane is still clear, "something" appears to move down toward the image at the aural axis, although the movement is not so much a movement of the image as a "sweep or shift of the visual schema" with respect to the images. The 'movement' takes *A*'s attention from the first image; but after she has looked back she finds the first image still near the median plane (16). Only once was there no appearance at all of movement: one image faded out first and then the other appeared.

Observer B does not in the majority of cases get the 'movement'. In 24 cases the tonal image in the median plane faded out completely while the image in the aural axis was appearing. He reports, however, 11 instances of a phenomenon of 'movement' toward the median plane, when the intensive variation is toward equality of the binaural ratio. These cases are of two kinds. (1) With the image at the aural axis the "sound-mass stretches out," becoming larger and less definitely localized until it reaches the region 30° from the median plane. Here it "pours in," while going out at the aural axis. During this interval, the "tone" stretches from the aural axis to 30° "like a double paddle, with nuclei at these points and an attenuated strand of image between." Then the image at the aural axis fades out while the image at 30° gets "clearer, contracts, and moves slowly toward the median plane" (4 cases in all). (2) The tone starts at the aural axis, and then passes smoothly to 30° *without traversing the intermediate spaces*; then it proceeds slowly to the median plane. *B* was unable to explain how the 30° and the aural axis could thus appear to lie adjacent in his localizing space. He thought that his cue to the 'movement' involves "something more than visual imagery" (7 cases in all.)

Observer C. At first the image moves a little from the median plane (30). Then this image dies out and another appears at the aural axis (30). In the early trials the sound has the appearance of movement from one position to the other, "as though passing through an hour-glass or pipe-system" [*cf. B*'s "double paddle" above]; nevertheless the image does not move between these points. Later *C* sees the phenomenon as "a gray screen between 20° and the aural axis in which the image at 20° oozes out slowly while the image at the aural axis grows clearer" (4).

Observer D. The image remains in the median plane for a time and then moves slightly to one side (20). Then sometimes the image, with its accompanying tone, gets gradually weaker, while an unclear, diffuse "sound-mass" collects at the aural axis (13). Rarely in these cases it appears as if "something had slipped" from the frontal region down to the aural axis (2). At other times, however, a "cloud of sound" gathers at the first image on the side toward the aural axis, "stretching out vaguely" toward the axis (7). Subsequently this "cloud draws up" about the image at the aural axis (7). The total phenomenon gives the impression of movement without actual movement.

TABLE III

Average localization with open ears of frontal and lateral images with electrical variation of binaural intensive ratio. Phase approximately equal. The localization of he frontal image is shown at the right of each cell of the table; the lateral image at the left.

Rheostat Scale (mm.)		L148	L142	L136	L130	L105	R20	R80	R110	R130
Electrical intensive ratios		75:1	29:1	18:1	13:1	5.5:1	1:1.3	1:3.2	1:6.2	1:13
Observers	*A*	L90	L89 L43	L88 L35	L76 L28	L10	R8	R84 R22	R75 R30	R89 R36
	B	L82	L80 L32	L9	L7	R8	R70 R29	R81 R36	R80 R40	R90
	C	L90	L86 L6	L85 L6	L72 L5	0	R4	R5	R90 R7	R89 R7
	D	L90	L90 L7	L90 L5	L4	0	R4	R90 R5	R89 R6	R89 R7

TABLE IV

Average localization with open ears of frontal and lateral images with electrical variation of binaural intensive ratio. Left tone leading in phase. The localization of the frontal image is shown at the right of each cell of the table; the lateral image at the left.

Rheostat scale (mm.).		L148	L142	L136	L130	L105	R20	R80	R110	R140
Observers	*A*	L90	L89	L88 L61	L86 L50	L85 L44	L26	L9	R1	R89 R40
	B	L88 L37	L89 L36	L87 L31	L90 L29	L16	R20	R84 R27	R89 R36	R90
	C	L90	L90 L42	L90 L40	L85 L38	L32	L5	L1	R1	R90 R5
	D	L90	L90 L50	L90 L48	L90 L41	L40	L10	R90 0	R90 0	R90 0

Series IV: Discrete Variation of Binaural Ratio with Phase-Difference throughout Complete Intensive Range

In order to obtain some information concerning the relation of the effect of the variation of phase-difference to the effect of the variation of intensive ratio, we repeated the experiments of Series II with the left tone leading in a phase an amount necessary to bring the localization of the image to the region of 'left 30°-40°.' The change of phase was accomplished by shifting the receivers, still one-half wave-length apart, with respect to

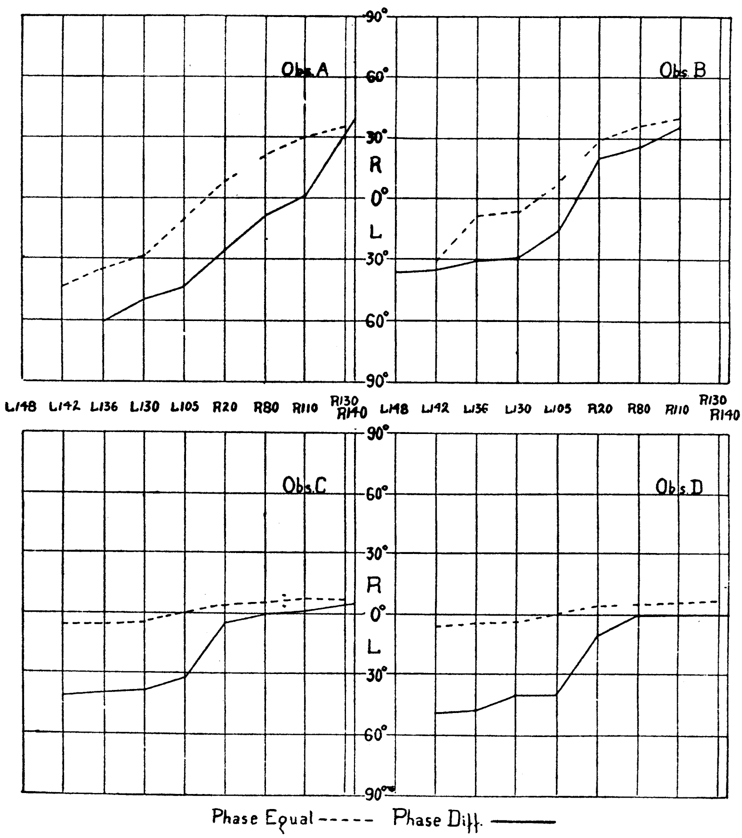

Fig. 6. Open ear localization. Graphs for four *O*s, showing localization (ordinate) as a function of binaural intensive ratio (abscissa). The abscissa values are settings of the rheostat controlling the relative intensity of the two sources of sound. See text and Tables III and IV. The dotted line is for the two tones approximately in phase, and the solid line for the left tone leading in phase.

the *O*'s head. This shift resulted also (presumably) in a slight intensification of the left source of sound, since this receiver was now nearer the head. The intensive difference is, however, to be thought of as having a small effect in comparison to the effect of the displacement of phase.

The observations are only slightly different from those of the three preceding series and do not alter the general conclusions. The frontal image shifts from 'left 47.5°' to 'right 20°,' the average of the four *O*s. It is never confused with the lateral image of the aural axis, but when it has attained its extreme lateral position all the *O*s report a peculiar unexplainable disturbance, as of sound widely distributed in the region separating this image from the image in the aural axis (see the introspective analyses: Series III, p. 205). The numerical results are shown in Table IV. The average of the mean variations for the localizations of all *O*s is only 3.2°.

Fig. 6 shows the effect that the introduction of a displacement of phase has upon the function that localization is of the intensive binaural ratio. The graphs of the figure show for each *O* the average localizations of the frontal image when there is no difference of phase (Series II: Table III) in comparison with the average localizations when the left tone leads in phase (Series IV: Table IV). It will be noted that in general the effect of introducing a phase-difference is simply to shift all localizations for a given binaural ratio toward the side of leading phase. In the cases of *C* and *D*, who show very little variation in localization when the phase-difference is zero, the variation is increased when the left tone leads in phase. This variation occurs on the side toward which there is greater latitude because of the change, *i. e.*, away from the shift due to the change in phase-relation.

The positions of the lateral image are not shown in Fig. 6, because this image always lies close to the aural axis.

The introspections show that where single images are reported the schema for localization for each *O* is that reported in the localization of a pure tone (pp. 187 ff.), and that the schema for double localizations is that described in the localizations of a tonal complex (pp. 198 ff.). In the present case, however, one of the images does not appear to move.

The following introspection by *B* sums up the situation nicely. He gives five other similar reports; and *A*, *C*, and *D* also report similarly although less fully.

"A very difficult localization. The tone at first was visualized indefinitely at my left between 90° and 30°. I do not mean that the visual images stretched from 90° to 30° for each image was small, subtending an arc not over 8°. The trouble was that I could not get the schema of reference to come into the visualization clearly. For a long time I sought (=eye-kinaesthesis of sweeping over the arc) for the place. *E. g.*, first I would

visualize the 90° position clearly. In doing this I could not see the tone! When I got the tone brought into the visual imagery, the imagery of the schema of reference would slip away. I would know that the tone was about 90° (*i. e.*, eye-kinaesthesis the same), but would not feel sure of the localization since the schema of reference was not visually clear. Then I would sweep through a small arc upward and the visual image of the tone would follow. About 30° this visual image would disappear and the visual image of the schema come in. Thus I got to know that the tone was between 90° and 30° without being able to say where. It also appeared as if 90° and 30° were only about 20° apart, since the sweep from one to the other was so small. I kept this chase up for a long time without getting the localization definite. Then I tried hard to see if I could get the visual image of the tone to come in while I had a clear image of 90° on the schema of reference. Soon I succeeded. The tone was distinct at 'left 90'.

While I fixated the tone here I became aware of another tone of the same auditory quality higher up on the schema of reference. I imaged it as in indirect vision. I turned my imaginal eye to it and saw it clearly, smaller than the other tone. At first it was unlocalized (indirect vision), then I got in rapid succession a number of visual localizations of it at about 40° to 30°. Finally the 30° reference became distinct. (This is an inadequate description of a long and very complicated consciousness, which is, however, a consciousness typical of the equivocal judgments that occur in these critical regions.)"

Supplementary Tests of the Rôle of the Binaural Ratio

We have found, when the binaural intensive ratio is altered, that the frontal image is limited in its range of movement, and that the lateral image, when it occurs, maintains an approximately fixed position. When both images are observed 'simultaneously', they may appear to be connected across the intervening space by "attenuated strands" (*B*) or "shooting streaks of gray" (*D*), or the connection may consist entirely in the fluctuation of attention between the two images (*A*, *C*) accompanied by eye-movement. If, with the stimulus sounding, one of these images appears when the other disappears, the *O* may experience a 'movement' from the one position to the other; it is not necessary, however, that this 'movement' should be anything more than a meaning applied to the successive occurrence of the two localizations. Except in this sense, no intensive difference is great enough to bring the frontal image near the aural axis. What happens ordinarily is that the frontal image becomes weaker as the lateral image becomes stronger, and that in this transition the auditory core, to which the visual image is the localizing context, seems to "detach itself slowly and subtly and to become attached" to the lateral image. Such a discrete shift of context may readily give the illusion of a continuous movement of the tone, especially if the localizations are not being made under an introspective *Aufgabe*.

There are some incidental tests which the writer has performed and which support this general conclusion concerning the effect of variation of the intensive ratio upon the localization of the tone. These tests are as follows.

(1) Series III in an abbreviated form was repeated for three *O*s, who, however, held the two telephone receivers close to the ears. The results, with the receivers thus placed, were exactly the same as those reported for Series III, (*q. v.*, p. 240 ff.).

(2) The intensity of the sound in one receiver was varied continuously by inserting into the circuit of one receiver an inductorium and varying the intensity inductively. The results of the localization of the image were again the same as in series III (3 *O*s).

(3) Three *O*s in localizing with closed tubes were asked to pinch one of the rubber tubes leading to the stethoscopic binaurals, after the appar-

atus had been set so that the image was localized in the median plane (phase equal). They all reported that the original image continued in the median plane until it disappeared. Meanwhile a second image gradually appeared near the aural axis. By careful manipulation of the tube these *O*s were able to find a condition (amount of pinching) under which both images were simultaneously observable.

(4) In open-ear localization with telephone receivers the image is always localized in the median plane when the *O*'s head occupies the position that corresponds with one of the maxima of the standing wave set up between the receivers (*q.v.*, p. 188). With a tone of about 700 d.v. and the *O*'s head in the position of one of the maxima, the receivers were moved one-quarter wave-length to one side. In this position the intensities of the two sources are approximately equal at the two ears, since the center of the head is now at a node of the standing wave; and, since the intensities are equal, the localization should be median. The *O*s, however, do not find a median localization, but experience the phenomenon that we have described as a 'balance' of intensities. The tone is heard on both sides at once and the image differs in extent, volume, timbre and intensity from the image of the median localization. If it be objected that this movement of the receivers does alter intensity slightly, since one ear is now nearer its receiver than is the other ear, it may be replied that the difference is inconsiderable in effecting localization, since, if the difference is made even greater by moving the next maximum to the center of the head, the *O* again gets a median localization.

Difference of Phase vs. the Binaural Ratio

We have already seen (p. 200 ff.) that the outstanding problem of binaural localization is the determination of the relative rôles of difference of phase and of difference of intensity in fixing the localization of the tonal image.

Rayleigh,[51] as we have seen, came to the conclusion in 1907 that the localization of low tones is a direct perception of difference of phase, whereas the localization of high tones (above 768 d. v.) is dependent upon intensive differences. Stewart[52] similarly holds that intensity is not to be considered as "an important factor in localization of pure tones" between 256 and 1024 d. v. Stewart found that when the intensity at one ear was diminished the image, originally in the median plane (equal intensity and no difference of phase), was usually displaced from the original position an amount depending upon the pitch of the tone and upon the particular *O*.

There is an early paper by Thompson[53] in 1878 which indicates the importance of phase-differences as effecting localization, although Thompson also noted the effect of intensity. He noted the change in localization of the tone when the connections to a telephone receiver at one ear were reversed while the connections to a receiver at the other ear remained unchanged.

In recent literature there is a tendency to consider intensive differences as mediating a rough localization and differences of phase a fine localization. Thus Bowlker[54] believes that "in the case of the higher notes—perhaps in the case of all notes—the zone or arc in which the sound-image appears is settled by the relative intensity at the two ears; the actual position of the images within this zone being produced by phase-difference at the ears." Klemm[55] found experimentally that, for sounds of short duration, the in-

[51]Rayleigh, *Phil. Mag.* (6 ser.), 1907, 13, 214-232.
[52]Stewart, *Phys. Rev.*, N. S., 1920, 15, 425-445.
[53]*Op. cit.*
[54]Bowlker, *op. cit.*, 327.
[55]Klemm, *Arch. f. d. ges. Psychol.*, 1918, 38, 88-91.

tensive differential threshold was significantly greater than the directional differential threshold for localization; that is to say, the image may move a distinctly noticeable distance in localization without the difference in intensity at the two ears becoming distinguishable.

The upholders of the binaural intensive ratio as the primary condition of localization cite the work of Matsumoto[56] in 1897. He used two telephone receivers, one at each side, simultaneously actuated by a 250 d. v. fork. When the relative intensities were altered the tone was variously localized about the head. These results seem to be inconsistent with the findings of the present paper. It must be remembered, however, that Matsumoto's tones must have been relatively impure, whereas ours were relatively pure in spite of the presence of the second partial in them. The addition of partials or noises to the fundamental alters conditions in an unpredictable manner. When phase is varied with an impure tone the various partials swing through different arcs to their respective angular limits (*cf.* p. 198 ff.); the relation of intensive change to the shift of the partials of a clang or the shift of different tones of different pitches is not known. Moreover, it may be true that Matsumoto did not always avoid varying the relative phase of his sources of sound, for he used an inductorium, the induction of which may have altered the electrical phase of the current. The greatest difference between the present experiment and Matsumoto's, however, lies in the lack of the introspective attitude on the part of Matsumoto's *O*'s. Our results have shown a certain amount of movement of the image about the median plane when the binaural ratio was altered, and they have shown that the tone (the 'second' image) 'reaches' the aural axis when the intensive difference has become great. Our introspections indicate, however, that the shift of the tone to the aural axis is discontinuous; it passes through a stage of equivocal localization where it is diffuse, scattered, or doubled. Matsumoto had no introspective check upon the nature of his *Os*' images; there is no certain way of telling whether the change for them was continuous or discrete.

In general then, it appears that a variation of the phase-relations of a tone at the two ears may lead to a continuous change in the localization of the tone, but that the variation of the intensive relations leads to a change that is continuous over a small region and discontinuous in its maximal change. Quantitative data, taken without introspective regard to the nature of the image of localization, may give the appearance of a continuous change of localization when the intensive relations are altered, because in the equivocal cases, where the discontinuity appears, an image that is double or scattered may be 'compromised' by being reported as localized at its geometrical center.

Conclusions

This study is a report upon the binaural localization of tones by four observers.

All these observers localized the tones in visual terms by placing a visual image that stands for the tone within a visual schema that represents the field of space. The analyses of the process of localization are given on pp. 186 ff., 198 ff.

The first part of the study shows that localization may be a function of the phase-relation of the tones at the two ears when the tone is conducted to the ears through closed tubes. The

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[56] M. Matsumoto, Researches on Acoustic Space, *Yale Psychol. Lab. Studies*, 1897, 5, 1-75.

nature of the function is shown in Fig.. 1, and the results of this section are summarized on pp. 187-188.

The second part of the study exhibits localization as a function of phase-relation when the sources of sound are on either side of the head and the ears are open (no conducting tubes used). It appears in these series that the first and second partials of a tonal complex may be simultaneously localized and that each then follows the law of phase-difference independently of the other. The functions are shown in Figs. 2, 3, and 4, and the results are summarized on pp. 198-200.

The last part of this study shows the dependence of localization upon the intensive differences of the tones at the two ears (binaural ratio). It appears that with intensive variation the localization may move slightly, but usually remains in the region of the median plane of the head, except that with extreme intensive variation localization appears at either side of the head near the aural axis although it does not move there continuously. The shift of localization due to intensive change is thus discontinuous and not regular as it is for change of phase. It would seem that difference of phase is thus a more effective factor in determining localization than is the binaural ratio. These results are shown in Figs. 5 and 6 and in Tables III and IV, and the issue is discussed on pp. 209-211.